International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 10, Issue 2, Apr 2020, 1385–1398

INNOVATIONS IN COLD - WORK TOOL STEELS

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ABSTRACT

Tool and die steels are essential for nearly all industrial sectors, hence they are being used to shape all articles that are present around us. Tool steel refers to a spectrum of plain and medium or highly alloyed ones that are particularly tailor - made for specific purpose. Their performance come from their special microstructures (carbides and martensite) which assure resistance to adhesive and abrasive wear as well as galling, and their ability to maintain a cutting edge at severe adhesive forces. As a result, die and tool steels are widely used as a informing and shaping entity of other metals and materials. Many types of tool steels are being applied in forging, rolling, cutting, pressing and extruding of metals and other materials. Their use in manufacturing injection molds is outstanding due to their high resistance to adhesive and abrasive wear, which is a vital and important criterion for a mold that would be used to produce thousands of products or parts.

The conventional production of tool steels is through normal steelmaking route, ingot casting or Continuous Cast (CC), annealing and final inspection. From these products, tools and dies are manufactured through traditional machining operations using lathes, drillers, CNC machines, wire cut or EDM processes.

Over the past years, the so called composite Powder-Metallurgy (PM) and spray forming technologies have been developed for implementation in the industry and is suitable to produce high alloyed tool steels on an industrial scale. The metal spray formed tool steel parts proved to have homogeneous, uniform and fine microstructure, if compared with PM or conventionally produced cold-work tool steel especially in texture and mechanical properties. Industrial applications advocate that tools made using spray formed steel had higher performance and life time than those produced through conventional route.

High toughness is required in case of steel grades used for pressing dies which depends on contents of alloying elements (chromium, molybdenum, vanadium and tungsten). In case of drop forging dies, wide properties are required and the standard steel grades are different from each other according to their usage in specific type of die or tool parts. Balanced combination of strength, toughness, adhesion resistance and other properties are required. Dies produced using PM or metal spray forming are tested in as forged conditions and it was found that the lifetime of the dies is increased with an average by 50 % or higher than that obtained from the conventional standard tool steel.

KEYWORDS: Tool Steels, Hot Working, Hot Deformation, Electroslag Refining, Powder Spraying, Powder Metallurgy, Nano-Metallurgy, Heat Treatment, Microstructures & Innovative Tools

Received: Mar 10, 2020; **Accepted:** Mar 30, 2020; **Published:** Apr 17, 2020; **Paper Id.:** IJMPERDAPR2020131

Original Article

1. INTRODUCTION

Tool and die steel family as per (AISI, ASTM and DIN) standards are designed to have hard, well distributed carbides in a matrix of tempered martensite with some retained austenite. Tool steels are superior quality steels produced with intended specific chemical composition to suit specific requirement and to develop mechanical

properties suitable for cold forming and machining other metals or materials. The chemical composition of such steels has high carbon content (0.5 to 2.0%) to form ledeburitic carbides with other alloying elements such as chromium, molybdenum, tungsten and vanadium.

Due to their superior adhesion and abrasion properties, die and tool steels are used in coining, machining, cutting, and pressing other metals and materials in cold basis. Meanwhile, special hot work die steels (0.3-0.5%C) are being used in branches like injection molding and die casting. Such molds are subjected to severe abrasion during production of thousands of shapes.[1,2] To ensure success of a specific die usage, sophisticated die type selection, well chosen implementation route and suitable mechanical properties through selected cycles of heat treatment, are keys to success of dies or tools.

Cold work tool and die steels having carbon content between 0.5%, 2.0% and alloyed with other alloying elements (Cr, Mo, W. etc) are produced using controlled steelmaking technologies to set the required quality. Following suitable hardening process for every steel type ensures the precipitation of chromium carbides or carbonitrides in their matrix which plays an important role to define the qualities of die and tool steels. The alloying elements that contribute to super performance are Cr, W, V, Mo, and Nb, however every element behaves separately in effecting in type and amount of carbides that define the life time of tool edge[3,4].

The presence of such high carbon and alloying elements refer to the obligatory implementation of specific heat treatment cycle that produces at the end of the required hardness and toughness. However, Mn and Si have to be kept at the minimum level required to overcome their affect during treatment. Die and tool steels international standards are numerous and many types of cold-work, hot-work, high-speed and maraging tool steels are well defined as in DIN, AISI, AFNOR and JIS standards. The specific tool or die selection depends on cost, working temperature, required surface hardness, strength, shock resistance, and toughness requirements.[5,6]. Undoubtedly, this group of steels can be classed among the biggest production tonnage used for tool manufacture, because they do not contain expensive alloying elements and are reliable to be water quenched without any remarkable distortion after heat treatment. It is used for all types of blanking and forming dies, gauges, etc. [7-9]. Implementing new production technologies of tool steels results in advanced materials, and easily lowers the maintenance costs.

Die and tool steels are being produced in tonnages using the traditional steelmaking processes and are normally delivered in soft annealed condition to make them conducive for handling (cutting, machining, shaping) before the final hardening process. The soft annealed microstructure consists of pearlite, retained austenite and some bainite matrix in which carbides are embedded [12, 13].

This review article aims to emphasize the importance of cold work tool & dies steels and projects of the recent developments in their production processes. Comparison between the conventional and recent advanced production processes as well as evaluation of the microstructures of these steels is also emphasized with relation to heat treatment cycles applied.

2. RANGE OF ALLOYING ELEMENTS

The mechanical properties of cold work tool and die steels depend not only on their chemical compositions but also on their microstructures created from hardening process applied. The way of quenching and tempering of tools defines the success of chosen heat treatment cycle. Differences between composition, properties and applications of cold work steels

are noticed as follow:

2.1 Cold-Work Die and Tool Steels

According to the international American Iron and Steel Institute Standards (AISI), the cold-work die and tool steels are divided in to the so called water quenching types or W-series, oil quenching types or O-series, and the air or oil quenching types or A and D-series.[14]

2.1.1 W-water Quenched Group

The die and tool steels that alloyed only with high carbon content without addition of another alloying elements like Cr, Mo, W, and V are called W-group tool steel which acquires its mechanical properties after Water-Quenching from their austenitizing temperature; they are merely plain-carbon steels. This group of tool steels is produced in tonnages and widely used than the alloyed groups because of their low production cost.[14,15]

2.1.2 Oil-Quenched Group

The oil quenched series includes all the steels like O1, O2, till O7 steels. Table1 projects the composition and usage of some of the above mentioned tool steels. All steels in this group are typically hardened at 800°C, oil quenched such as O1, O2 and O7. All the steels are quenched in heavy oil and then low-temperature tempered at 250°C[16,17]

Table 1: Composition and usage of some Oil-Quenched Tool Steels

Grade	Composition	Notes
O1	0.80%C, 0.9–1.2%Mn, 0.80%Cr, 0.70%W, 0.30%Si, 0.20%V	Used for gauges, cutting tools, and knives. It can be hardened to 64 HRC.
O2	1.2%C, 1.0% Mn, 1.5% Cr, 0.30% Si, 0.20% V	Used in cutting tools, woodworking tools and knives.
O6	1.6% C, 2.0% Mn, 1.0% Si, 0.4% Mo	Resistant to adhesive wear and galling.

2.1.3 Air-Quenched Group

The first air-hardening-grade tool steel was Cr- steel, which was known as *air-hardening steel* at the time. Table 2 projects the composition and usage of Air-hardenable steels. The application of air quenching in D or A-tool steels assured good hardenability, negligible distortion of the tool and minimal changes in dimensions, because of their high alloy content. [18-20] Table 2 illustrates some types and application of Air-hardenable tool steels.

Table 2: Composition and usage of some A-series Tool Steels

Grade	Composition	Notes
A2	1.0%C, 1.0%Mn, 5.0%Cr- 1.0%Mo, 0.15–0.50%V	Used in fin blanking, punching, cutting, thread rolling and mold manufacturing
A3	1.3% C, 0.5% Mn, 5.0% Cr, 1.4% Mo, 1.4% V	Nearly same usage with high effectiveness
A10	1.70% C, 1.8% Mn,1.0% Si, 2..0% Ni, 1.8% Mo	Used for gauge tools, razors, shearing tools, and punching dies

2.2 D-Series (High carbon-chromium)

The D series of the cold-work class of tool steels, which originally included types D2, D3, D6, and D7, contains between

10% and 13% chromium. Table 3 shows features of D3-tool steel as an example from the oil or air quenched tool steel series. Due to their high alloy content, these steels have massive carbide distribution within a hard martensitic matrix that ensures excellent hardness even at high temperature up to 400°C. Accordingly, these tool and die steels are extensively used in different applications like forming and cutting dies, extrusion, die blocks, and wearing cavities in brick manufacturing. The D-tool steel is also used in engineering industries that deal with production of house ware products like stoves, fridges and many other appliances. [21, 22]

Table 3: Features of widely used D3-D5 Tool Steel

Grade	Composition	Notes
D3	Carbon 2.0-2.3%, Chromium 10.0–13.0%, Molybdenum 1.0%, Tungsten 0.9%, Vanadium 1.0%	The cold -work D2 tool steel is widely used in the production of wearing plates used in cavity-forming bricks, press forming heads, cutting tools, knife and razor blades.
D5	Carbon 14-1.6%, chromium 11-13%, Molybdenum 1.0%, Vanadium 1.o%, Cobalt 2-2.5%	The cold-work D5 tool steel is widely used in severe applications where long life cutting edge is needed.

The unified standards UNS, American iron and steel institute standards AISI and standards of automotive engineers SAE classified the cold work tool steels as given in table (4).

Table 4: Cold Work Tool Steel types, according to the US [UNS, AISI and SAE] classification [22]

Tool Steel Type	Prefix	Specific Types
Cold Work	W = Water Hardening	W1, W2, W5
	O = Oil Hardening	O1, O2, O6, O7
	A = Medium alloy Air Hardening	A2, A4, A6, A7, A8, A9, A10, A11
	D = High Carbon, High Chromium	D2, D3, D4, D5, D7

3. PRODUCTION OF TOOL STEELS

Tool steels are being produced in many steel mills using the conventional well established technologies, but there are some advances in their manufacturing processes. In the following paragraphs, a comprehensive up to date survey is made to illustrate the differences and advantages of various steelmaking processes of die and tool steels.

3.1. Conventional Production

Conventional steel making steps used to produce such steels are:

- Primary Melting
- Continuous Casting or Refining by Electroslag Melting (ESR)
- Rolling or Forging and Hot and Cold Drawing
- Cast-Tooling

3.1.1 Primary Melting

Melting of tool steels starts initially from charge constituents which are composed mainly of shop scrap, purchased scrap or starting from the ABC-steelmaking using hot metal and ferroalloys (LD, BOF, EAF). The majority of tool steel production is done through Electric Arc Furnace (EAF) melting aided with oxygen jets to enhance melting and helping in oxidation of some unwanted impurities. The composition of the slag is very important to absorb any unwanted sulphides and oxides during the mutual reaction at the metal/slag interface. After complete melting and composition adjusted, the melt can be transferred to the outside-furnace refining unites, like vacuum, stirring, heating and final composition correction. This process is known as secondary steelmaking or steel refining. The refined metal is then transferred to be cast into ingots or continuously cast to billets or slabs. The steel ingots or slabs are usually slowly annealed to prevent any unusual splitting or cracking. [23, 24]

3.1.2 Electroslag and Vacuum Refining

One of the currently used processes to refine and homogenize the produced steel ingots is the so called ElectroSlag Remelting (ESR) as shown in Figure (1). In this process, one or more ingots are to be melted and passed through liquid synthetic slag with a special composition depending on the chemical reactions to be applied. The ESR produced refined ingots are characterized with smooth surface, homogenous texture, segregation free, porosity free and smooth solidification contours along the length of the ingot.[25,26] Of course and from the economical point of view, the application of electroslag remelting adds more expenses to the final steel price per ton, however for many reasons, tool steel quality and its specialized applications ESR is worth considering. New advances are made to increase productivity of that process by increasing the rate of melting using more efficient electricity supply and combined series of ESR units up to 5 stands, which is called ElectroSlag Rapid Remelting (ESRR). [27] Application of Vacuum Arc Remelting (VAR) beside the ESR is always possible and this is only the decision of the steel mill according to their economical point of view. The resulting steels are characterized with smooth surface, homogenous texture, segregation free, porosity free and smooth solidification contours along the length of the ingot, has a refined microstructure together with excellent chemical uniformity. Figure2 illustrates the configuration of ESR equipment[28].

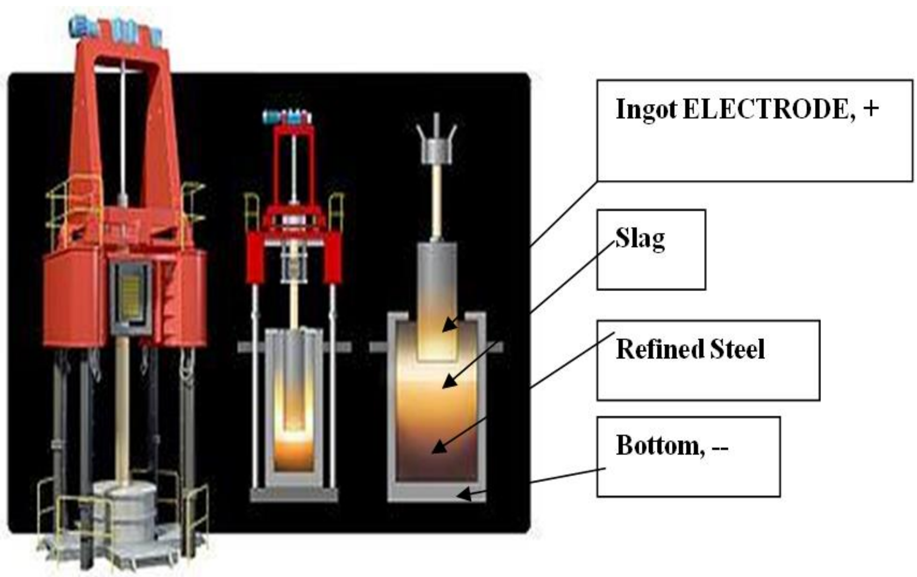


Figure 1: Electroslag Refining System.

3.1.3 Metal Working

The produced die and tool steel ingots, billets or slabs are then subjected to forming process or metal working using rolling or forging mills. Before metal working, the ingots are slowly heated in continuous pushing electric furnace to avoid any abrupt temperature change through ingot thickness or metal surface oxidation at the working temperature (1200-1250°C), Thus the steel ingots get ready for rolling or forging. In modern steel manufacturing, many rolling passes are used in a row. The metal working process is thoroughly controlled and automated by computer programming and measuring devices to control the size tolerance and surface quality of the produced tool steel bars or squares or even coils and plates.

Many clients prefer the usage of tool steel forged products, specially used in heavy blanking or pressing dies for their excellent texture and homogeneous structure Figure 2 [29-31]

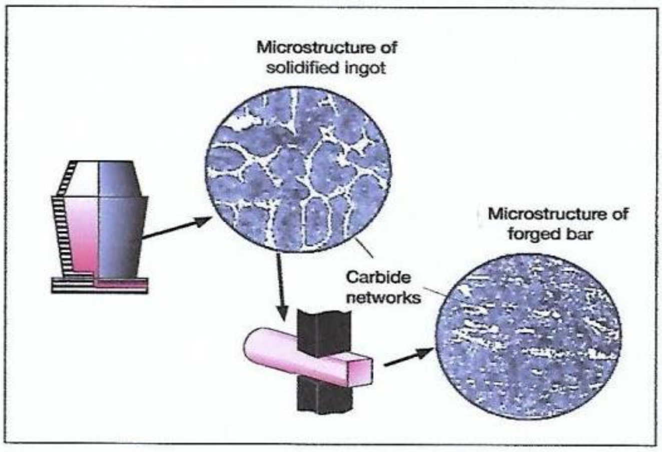


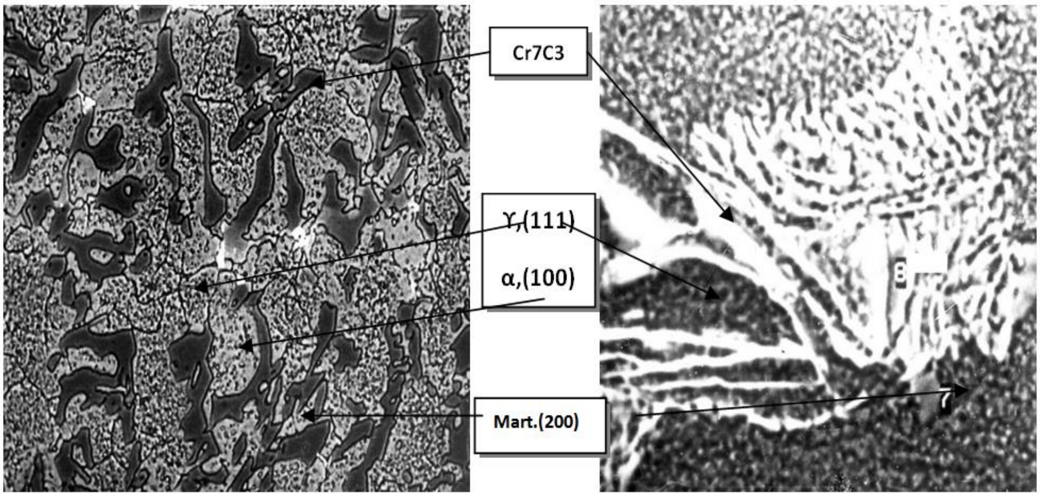
Figure 2: Break Down and Distribution of Carbides in Conventionally produced Tool Steel.

3.1.4 Continuous Casting

Continuous casting of tool steel, like all steels, can be continuously cast to billets or slabs for economical reasons. The molten metal is poured into the casting ladle and then transferred to the continuous casting station where the metal is poured into the tundish and then flows through water cooled molds to shape slabs or billets strands after cooling. Following casting, the billets are slowly soaked in pushing electrical furnace as mentioned before at 1200°C to be annealed and then forged or rolled to the desired sizes. [32]

3.1.6 Cast Tooling

One of the recent techniques to produce near net shape tools is cast tooling, where tools are being produced using investment casting. Many researches and industrial production of tools and others were performed at Labs of the Central metallurgical R&D Institute. The recent research concerning cold work tool steel cast tooling is conducted by steel technology Laboratory, especially to refine the ledeburitic carbides of D2-tool steel from massive flakes and stringers to scattered globules of carbides. This was accomplished using treatment of the molten steel with FeSiMg, where the generated gas alters the morphology of carbides during solidification as shown in Figures 3 and 4.[34]



400x **2500x**

Figure 3: Microstructure of Slowly Sand-Cooled Cast D2 Tool Steel.

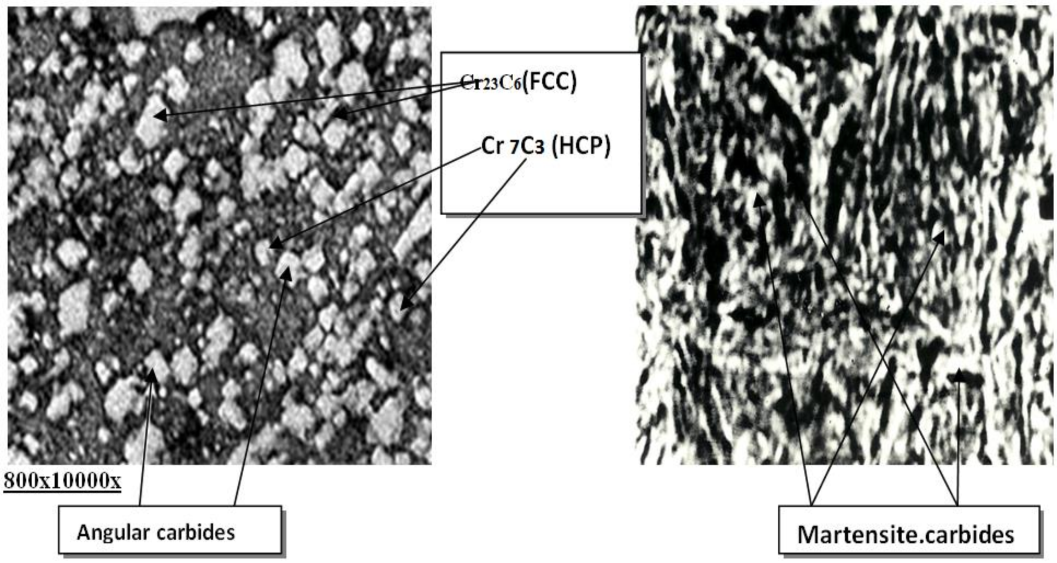


Figure 4: Distribution and Morphology of Carbides after treatment with FeSiMg.

3.2. Advanced PM Composite Tool Steel Production

Powder Metallurgy (P/M) is one of the recent processes used to produce highly alloyed tool and die steels and high-speed steels.[34,35] In traditional steelmaking process, the production of high-carbon, high-alloy tool steels pass through relatively slow cooling rates which result in the formation of undesirable coarse carbides together with severe segregation of elements. However, tools and dies having fine, uniform microstructures with good distribution of carbides can be produced using P/M which results in improved mechanical properties and machinability in the annealed conditions.[36,37] Figure (5) illustrates the flow of materials during implementation of the powder metallurgy P/M process to produce tool steel ingots or final parts.[38]. In this process, molten tool steel is sprayed using atomizer at high pressure of carrying inert gas or water jets, screened to size, milled to required grain size, compacted using Hot Isostatic Process (HIV) and then sintered at elevated temperatures (1200-1300°C) under vacuum to the final shape of required tools, as shown in Figure 6.

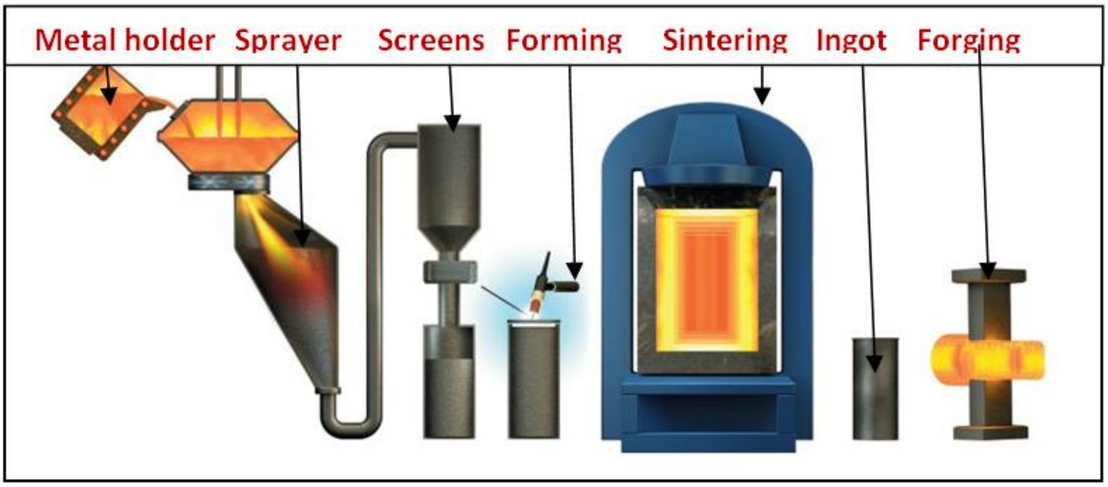


Figure 5: Process Diagram of Powder Metallurgy Technique.

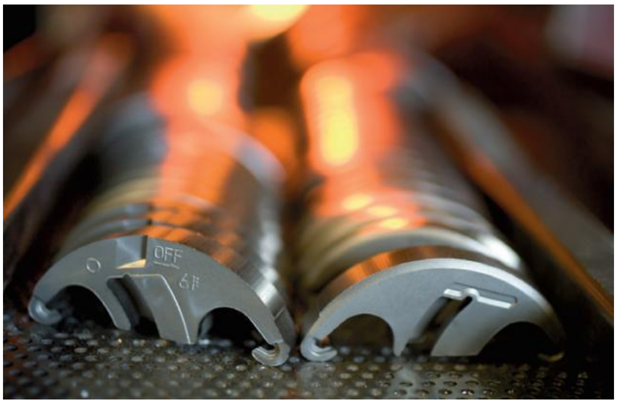


Figure 6: Sintering of Compacted Tool Steel Parts.

3.3 Advanced Metal-Spray Process

During the past decade, Spray forming process has been developed as a new era for tool steel production, which, today, is suitable to produce high alloyed steels on an industrial scale. Dan Spray [39] has opened the first industrial billet spray forming plant for specialty steels in Taastrup (Denmark). Edelstahl Witten-Krefeld GmbH-Germany has cooperated with Dan Spray Company, in order to evaluate the state of art of spray forming and to develop new spray formed tool steels [40].

The metal-spray process has still limited applications worldwide, but it is implemented in Japan and the UK. However, from the scientific point of view, it has tremendous technical and commercial potential when correctly applied. In this process, the melt of alloyed tool or die steels is poured directly from an induction furnace after compositional control into reservoir ended with injection nozzles and then blasted with high-pressure inert-gas atomization jets, causing the formation of a bulge containing small metal droplets, solidified fine particles and others in mushy state. The bulge is then collected on a rotating shaped form to shape final billets, hollows, special forms and sheets. The properties of dies and tools produced using the spray process are similar to those produced using powder metallurgy process P/M, hence the products have uniform distribution of fine carbides within a refined matrix. However, this process is currently not as economically competitive as P/M[41]. Table 4 illustrates some of tool steels produced using Osprey process. However, Figure (7) illustrates the flow diagram of spray process.

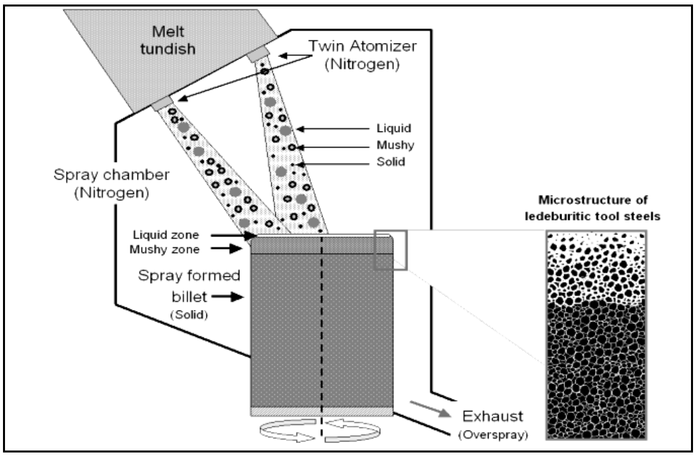


Figure 7: Process Flow Diagram of Osprey Production Technique.

4. HEAT TREATMENT & MICROSTRUCTURES

The heat treatment of produced tools and dies is a final vital important operation because it defines their mechanical properties. Faulty heat treatment means a tremendous loss for the production line. Before subjecting the products to a heat treatment cycle, always stress relief operation has to be followed, in which the machined or formed tools or dies have to be heated to about 550-600°C for 2 hours and then air cooled. The choice of austenitizing temperature (900-1100°C) is very important to avoid more grain gross at high temperatures or no complete transformation at low ones.

At austenitizing temperature, all the carbides are re-dissolved again into the austenite phase to form carbon saturated austenite FCC phase; this requires certain time of soaking at that temperature. The steel matrix is transformed from soft structure (ferrite, pearlite and carbide) to FCC single phase austenite, this means that the Iron atoms change their position in the atomic lattice and generate a new lattice with different crystalline structure. During rapid quenching of the tool, it cools down until it reaches a certain temperature, the martensite forming temperature where austenite begins to reject its carbon again, forming a very hard phase called maretnsite through a severe shearing reorientation of carbides and other elements.

The final structure after quenching is composed of hard massive martensite, some retained austenite and different fine or coarse ledeburitic carbides. This structure is heterogeneous and full of stresses and is very brittle. Volume changes and internal stresses can happen for the tool due to the rejection of carbon from austenite and formation of other phases. In case of heavy dies or tools cascade quenching can be applied where the cooling is interrupted at about 80°C for a 30 minutes hold to avoid cracks and further stresses. However, risk of distortion and minute cracks can be reduced by the so called martensite tempering or mar-tempering. In many cases, all the tools and dies are heated in vacuum furnace or salt bath before quenching, in order to avoid any surface oxidation and loss of some carbon and alloying elements at that area.

Tempering operation is the last step in heat treatment, where the tool or die is just transferred after martensitic reaction to be tempered. The tool is reheated at moderate temperature (250-400°C) depending on its composition. Hardening of tool steel should always be followed by reheating for tempering process. Low temperature tempering contributes to stress relief from martensite. Meanwhile, high temperature tempering enables the transformation of retained austenite to soft martensite contributing to more hardness, strength and light ductility. The overall tempered microstructure of the tool or die steel consists of tempered martensite, newly formed martensite, some retained austenite and different

Me3C, Me7C3...etc. carbides. Precipitation of secondary carbides during tempering is always beneficial to increase strength, hardness and adhesion resistance, however and for a specific purpose, certain hardness levels is required for each individual application of the tool or die.

Double and triple tempering cycle is used only in specific applications where toughness is not a matter, the tool or die is subjected to re-tempering to permit further reaction to convert retained austenite to martensite and precipitate secondary carbides, this would add an increment of hardness to the matrix. In some cases, refrigerating tools at low temperatures (under zero tempering) helps in rapid and full transformation of retained austenite to martensite. [42,43] Figure 8 projects the Time-Temperature-Transformation (TTT) diagrams for highly alloyed tool D- tool steel [44,45].

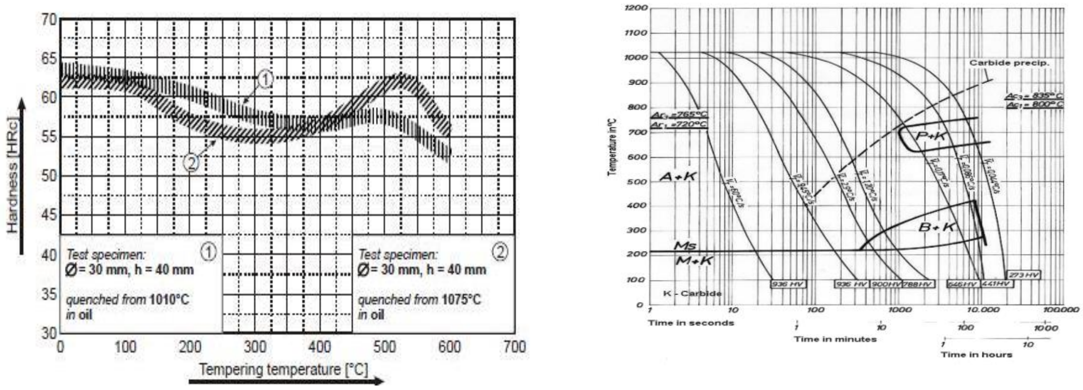


Figure 8: TTT-diagram of D2-cold work tool steel (1.5%C,13%Cr,1.0%V, 1.0%M0).

5. INNOVATIONS IN MICROSTRUCTURES

The main target of conventional composites, Metal spray and any other new production technologies of tool and die steels is to obtain the maximum optimized distribution of carbides in a refined martensitic microstructures. Unfortunately, this is not the case in conventional production route; Figure (9) projects the distribution of massive carbides in heat treated tool steel after forging in flow and cross directions. However, Figure (10) illustrates the microstructure of cold-work tool steel in the as sintered P/M and quenched condition. In Figure (11), the homogeneous distribution of carbides is clear in as sprayed samples, however the ledeburitic net of carbides can be more refined by slight forging of the tool steel.[46,47]

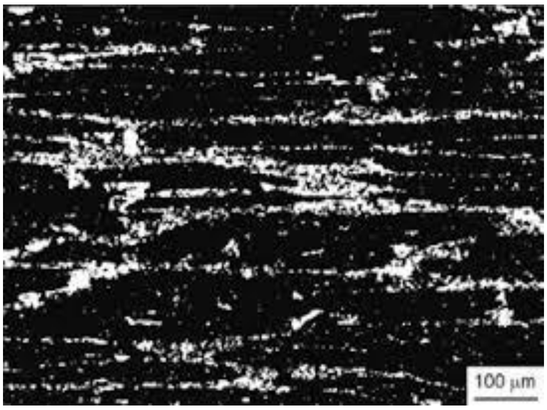


Figure 9: Carbide print in Conventional Forged Bars of D2-Cold-Work Tool Steel.

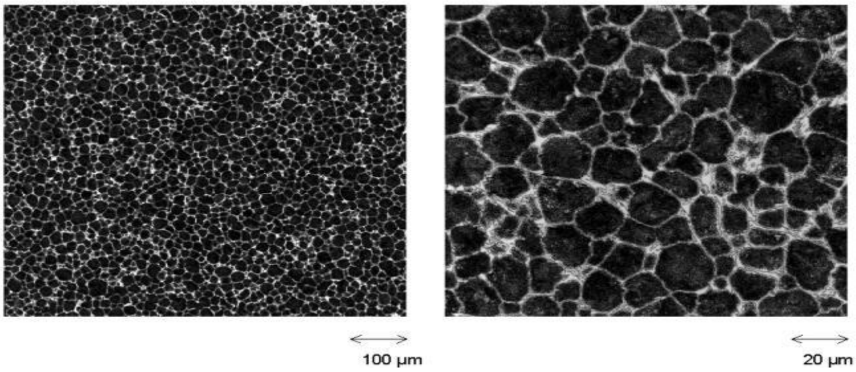


Figure 10: Microstructure of D2-cold-work Tool Steel in the as sintered (right) and Quenched Condition (left).

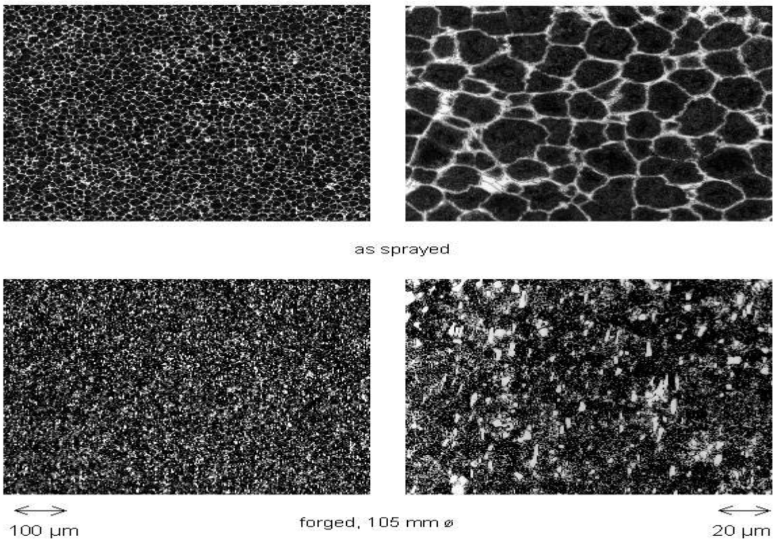


Figure 11: Microstructure of Spray Formed Billet of D2- Tool Steel.

6. CONCLUSIONS

- A comprehensive up to date scientific survey in the field of cold work tool and die steel production innovations, heat treatment and application design has been reviewed.
- The conventional production technology of such die and tool steels suffers the long –time process and the quality of product is more brittle before application, due to the presence of ledeburitic carbide net embedded inside the martensitic matrix.
- The cold-work tool steels produced using advanced powder metallurgy by compacting and sintering proved to improve the toughness and hence performance of the tools has improved.
- Implementation of the recent metal-spray process to produce such tool and dies steels proved to add more flexibility, toughness and homogeneity to the products.

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